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A method to estimate the environmental impact of an electric city car during six months of testing in an Italian city

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HIGHLIGHTS

- Environmental impact of electric vehicles with Plant-To-Vehicle approach.
- Electric consumption measured on board over 42 tests, with and without use of auxiliaries.
- Emission factors (g kWh^{-1}) for Italian power plants at full and partial loads.
- Electricity generation mix for each recharging event.
- Comparison with limits set by European legislation for CO_2 and pollutants.

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ABSTRACT

The present investigation describes the results of a research project (P.R.I.M.E.) aimed at testing the performance and the environmental impact of an electric city car in Italian cities. The vehicle considered in the project is the Daimler AG Smart ForTwo Electric Drive. A Smart ED vehicle was tested at the University of Salento for six months over different driving conditions (routes, traffic, use of auxiliaries). A data acquisition system has been designed on purpose and assembled on board to provide information about driving cycle and energy flows. The system was also used to evaluate the losses of energy during recharges due to the battery cooling system. The experimental tests were used to identify the average, minimum and maximum consumption of electricity in the Smart ED in Lecce according to driving conditions and in particular according to the usage of auxiliaries.

The measured data of electric consumption have been used to quantify the emissions of CO_2 and pollution of the vehicle using information about the Italian electricity production mix of each recharging event and the emissions factors of the Italian power plants with an innovative and comprehensive methodology.

1. Introduction

In the last fifteen years, the interest in hybrid and electric vehicles as a midterm solution for sustainable mobility has strongly increased. However, plug-in vehicles are still unable to penetrate the market for several technological limitations. This investigation considers only Battery Electric Vehicles (BEVs), i.e. vehicles moved by an electric motor with a battery pack as sole on-board energy source.

The main drawback of BEVs resides in batteries, which are still too expensive, too bulky and heavy due to their low energy density [1]. Moreover, they have an unsatisfactory life cycle and require long recharging times [1]. The reduced energy density of batteries limits the range of electric vehicles particularly when a large number of electric auxiliaries is used (like in modern cars) [2,3]. For this reason, it is important to quantify the electric consumption in the worst conditions in terms of driving pattern and use of auxiliaries [4]. Some works in literature investigate the consumption of BEVs with and without the use of auxiliaries. [5–9]. According to [5], the use of air conditioning can reduce the mileage of a vehicle (either electric or conventional) by 40%. However, the effect on pollutant emissions is not taken into account in these studies.

To evaluate the environmental impact of a vehicle, it is necessary to consider the correct energy pathway [4]. The well-to-wheel (WTW) analysis takes into account the total primary energy consumption yielded by the vehicle for each kWh of energy given at the

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wheels, including all the steps covered to fill the on-board energy tank (WTT) and the subsequently onboard energy conversion to move the vehicle wheels (TTW).

From a Tank-to-Wheel (TTW) point of view, a BEV does not produce either pollutant or greenhouse gases while the Well-to-Tank (WTT) emissions are strongly dependent on the electricity generation mixes of the country [10–16]. Doucette et al. [10] used numerical simulation of electric vehicles to evaluate the electric consumption and the corresponding emissions of CO_2 according to the electricity generation mixing of different countries. They found that, for countries with high CO_2 intensities (e.g. China and India), BEVs can actually have higher operating CO_2 intensities than similar ICE-based vehicles.

As for emissions, electric vehicles have a direct positive impact on pollution in urban centers having zero tailpipe emissions. However, BEVs do have an environmental impact because of the production of greenhouse and pollutant emissions during e electricity generation.

NO_x are dangerous for human health in urban environments but are also responsible for acid rains; Volatile Organic Compounds (VOCs) reduces productivity of agriculture [17]. For this reason it is important to evaluate the environmental impact of electric vehicles even if the problem of pollutant emissions is moved from urban centers to fossil fuel chimneys that are usually outside the cities.

Menga et al. [18] compared the emissions of battery electric vehicles with conventional passengers cars by considering literary values of consumption and average Italian generation mix for the production of electricity. However, the electric consumption of the Smart ED was found to be strongly affected by the use of auxiliaries [19] and weekly by the vehicle speed profile [20]. A complete approach (Life Cycle Assessment) should take into account also the emissions associated to the building and dismantling of the vehicle and to the production of the fossil fuels [17].

The present investigations proposes a methodology that takes into account the actual electric consumption measured on board, the losses of electricity in the grid and the losses during recharge due to the battery cooling system. The actual mixing of sources used to generate electricity for each recharge is used instead of average values [18]. Note that the analysis presented here is not a full WTW approach because the boundary for energy paths is set at the electricity generation plants. The recovery and transport of fuels and feedstock produce both greenhouse and pollutant emissions. While average values of CO_2 emissions in this path are available in literature [4], the upstream emissions of pollutant are not easy to quantify. For this reason, this investigation takes into account only emissions associated to the use of electricity with an approach that can be referred to as PTW (Plant-To-Wheel) like in the work of Blumsack et al. [21].

The investigation is part of a research project named “PRIME – Progetto di Ricarica Intelligente per la Mobilità Elettrica” funded by Italian Ministry for Environment MATTM (Ministero dell'Ambiente e della Tutela del Territorio e del Mare) and involves several industrial and academic partners. The goal of the project is to collect experimental data of mobility demand, fuel consumption and vehicle performance from a fleet of Smart ED sold to about 100 users in three different Italian cities and two plug-in electric vehicles at the University of Salento. The project also studies the behavior of customers, analyzes the impact of charging stations for electric vehicles on the stability of the electric grid and estimates the reduction of pollutant and greenhouse emissions.

The data of electric consumption shown in the present investigation were obtained on one of the 100 Smart ED vehicles that was tested at the University of Salento.

2. Testing of the electric vehicle

A commercial version of the Daimler AG Smart ForTwo ED vehicle (Smart ED) has been tested for six months (from May to November 2013) in Lecce, Italy, after being equipped with an on-purpose acquisition system to measure electricity flows in the vehicle during recharging and in motion. Smart ED is a BEV equipped with a 55 kW brushless DC electric motor, a 52 Ah lithium-ion battery and a final drive ratio equal to 8.67. More details on the vehicle can be found in Ref. [22] and in Appendix, Table A1.

All the recharges were registered thanks to the use of the smart Enel recharging station installed at the Department of Engineering for Innovation of the University of Salento [23] as described later in the paper.

The vehicle was tested in Lecce in different conditions of traffic and weather with a different usage of auxiliaries for a total of 42 tests. The details of the routes are shown in Table 1. The first route (mixed) was considered to move the vehicle from the Campus of University of Salento at Lecce to the city center. The second route is a ring urban itinerary in the center of Lecce. The third route represents a travel from the campus to a nearby city (Copertino) and back again. The fourth route (extra-urban) is an itinerary on the external orbital road around Lecce. The tests were also classified according to the auxiliaries power status (AC, heating, heated rear window and lights). The complete list of the tests is reported in Table A2.

2.1. Acquisitions on the BEV vehicle

A specific system was implemented on the Smart ED to acquire information about the vehicle functionality during recharging and in motion.

The system was designed to measure the current at positive pole of batteries and the current at positive pole of the motor. The difference between these two values gives an indication of the current used for the auxiliaries. Currents were measured with Hall Effect transducers (LEM HOP–300SB). These sensors give two voltage signals (from −5 V to 5 V) proportional to currents that are inputted to a National Instruments cDaq USB module. The losses in the vehicle controller were assumed to be independent of driving conditions and usage of auxiliary and, above all, to be negligible with respect to the current absorbed by the auxiliaries.

A GPS antenna allows the acquisition of information about the route and the time history of vehicle speed (driving cycle). From this operation it was possible to obtain other statistical information on the driving cycle like average speed, number of stops, average positive acceleration, etc.

Data acquired on board were stored through USB interfaces into a Netbook computer with a frequency of a record per second. Each record contains a timestamp (date and time), a sample progressive number, the time history of current outgoing battery, battery ingoing electric engine, GPS information (latitude and longitude) and GPS based speed. A set of flag variables, controlled by user, was also recorded to indicate status of each auxiliary (on/off).

Note that the proposed approach takes into account the efficiency of the motor and of the mechanical transmission to evaluate the electric consumption because the current is measured upstream of the motor.

The coulomb counting method is used for the estimation of the State of the Charge (SOC) of the battery. The coulomb counting method calculates the remaining capacity by accumulating the charge transferred in or out of the battery. This method is impractical for real-time SOC estimation in commercial vehicles because it requires long time monitoring and memorizing but

Table 1
Details of the routes.

Route	Description	Type	Season	Number of tests	Total distance [km]	Electric consumption [kWh]	Average consumption [kWh/100 km]
1	From campus to Lecce city center or vice versa	Mixed	Summer	8	73.1	14.4	19.7
1	From campus to Lecce city center or vice versa	Mixed	Winter	2	12.6	2.97	23.6
2	Ring urban itinerary in Lecce	Urban	Summer	16	126.9	25.1	19.8
2	Ring urban itinerary in Lecce	Urban	Winter	5	26.3	5.97	22.7
3	From Campus to Copertino city center and back again	Mixed	Summer	4	62.6	11.2	17.9
3	From Campus to Copertino city center and back again	Mixed	Winter	2	20.5	3.88	18.9
4	External ring of Lecce	Extra-urban	Summer	5	84.0	15.8	18.8
Total				42	405.9	79.33	19.5

convenient and accurate for the test of lithium-ion batteries. If fact, it is used to verify the accuracy of other SOC estimation methods [24].

For each test the following procedure has been followed:

1. Before starting the test, the initial SOC provided by the vehicle SOC indicator is read and stored;
2. During the test, the instantaneous current to/from battery is measured with a sampling frequency and stored;
3. The current time history is then integrated to obtain the electric energy used for the cycle;
4. The current to/from the motor is also measured to estimate the power used for the auxiliaries;
5. The difference between initial and final SOC is used to evaluate the electric consumption of the vehicle over the specific test.

The measured electric consumption of the Smart Ed is reported in Appendix A, Table A2 for each test. The voltage was assumed to be constant and equal to the nominal value of 320 V [22] for the application of the Coulomb counting method. In the post processing phase a voltage variation model related to SOC(%) was used to obtain more accurate values of power consumption. This model assumes that the voltage presents a linear variation around the mean value of 320 V with a minimum of 305 V with SOC = 20% and a maximum of 330 V with SOC = 100%. More details on the measurement procedure can be found in Ref. [19].

2.2. Measure of recharging losses due to battery cooling

Other tests were made during the recharging of the vehicle to evaluate the energy losses due to batteries cooling when the vehicle is in recharge. The recharging station used in this investigation is an intelligent model developed by Enel [20] to monitor the energy consumption of each recharge. Fig. 1 shows the time history of the battery current during a slow recharge performed in a very hot day. Note that the measured data show a linear trend in time of current which is negative because the battery is in recharge. Current decreases in absolute value from about 14 to about 11 A. However, three current pulses can be noticed. These are due to the cooling systems that was turned on three times. In the first and third starting, the cooling system requires a surplus of current of about 4A while in the second starting, the surplus is so high that it determines a change in the sign of the current (i.e. battery is in discharge even if connected to the charging station). This phenomenon determines a difference between the electricity measured on the recharging station and the electricity actually stored in the batteries. The tests have shown that the loss of electricity is in average 10% of the electricity at the station with a peak of 14% [19].

Note that the recharging losses described in this section are referred to the vehicle, not to the station. The losses of the recharging station will be taken into account as a further investigation if they will be found not negligible from measurements or literature data.

2.3. Analysis of the electric consumption

A detailed analysis of the electric consumption of the Smart ED is presented here on the basis of the experimental tests. The measured electric consumption versus average speed is shown in Fig. 2 for the summer tests and in Fig. 3 for the winter tests. The values measured by Freuer et Reuss [6] on the same electric vehicle (without auxiliaries) are also reported in Fig. 2 as a validation.

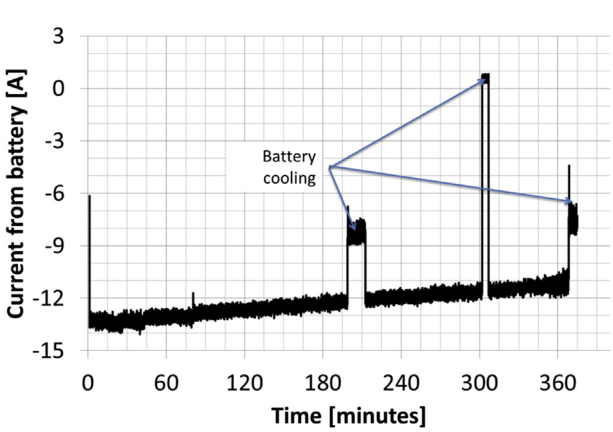

Fig. 1. Losses in the recharging process due to battery cooling.

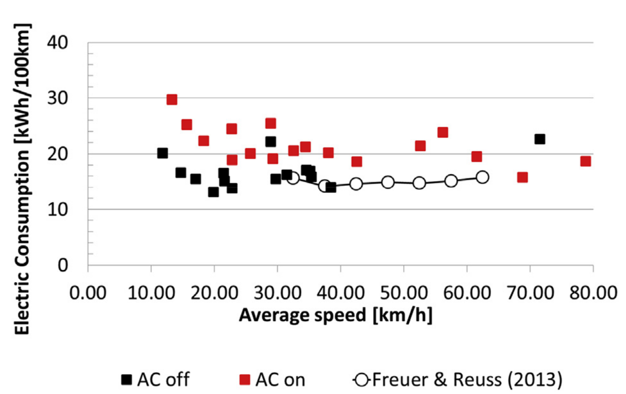

Fig. 2. Electric consumption versus average speed for the summer tests (with data from Ref. [6] for validation).

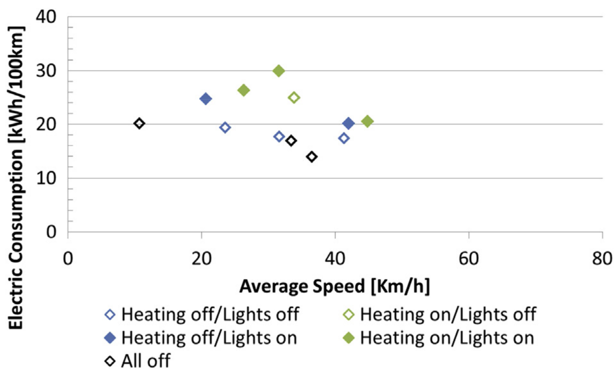

Fig. 3. Electric consumption versus average speed for the winter tests.

In summer, tests were performed with and without the use of Air Conditioning (AC). In winter, the auxiliaries taken into account were: lights, cabin heating and heated rear window.

Note that the consumption of the Smart ED is weakly affected by the average speed of the vehicle. In fact, there is no notable trend of electric consumption vs speed in Figs. 2 and 3. In particular, when auxiliaries are not used, the electric consumption is almost constant in all the speed range and the average values of electric consumption is 17 kWh/100 km (see Table 2 where the average values of electric consumption are reported according to the use of each auxiliary). This result is coherent also with measures on other electric vehicles in Ref. [23] and with the results of Freuer et Reuss [6]. The average values of electric consumption for each auxiliary and the corresponding over consumptions with respect to the "no auxiliaries case" are reported in Table 2.

When air conditioning is used, electric consumption shows a decreasing trend with average speed. Apparently, the effect of AC is higher at low speed. The average consumption with AC is 21.5 kWh/100 km (Table 2) that corresponds to a surplus of 21% with respect to the average consumption without any auxiliary. In the worst case, (urban cycle 28 with an average speed of 12.3 km h^{-1}), electric consumption with AC reaches 30kWh/100 km (+76% of the average value without AC).

The effect of winter auxiliaries on electric consumption is equally high with a peak of 30 kWh/100 km in the case of a test with average speed of 30 km h^{-1} (mixed cycle) and all auxiliaries turned on. In average, the heated rear window increases electric consumption by 7%. Lights have a quite strong effect (+24%). Adding cabin heating, the electric consumption is in average 34% higher than in the case without auxiliaries (see Table 2.)

Table 2
Average electric consumption for different usage of auxiliaries.

Auxiliaries	Electric consumption [kWh/100 km]	Over consumption [kWh/100 km]
No auxiliaries	17	0
Heated rear window	18.2	1.2 (7%)
Air conditioning	21.5	4.5 (21%)
Heated rear window & lights	22.4	5.4 (24%)
Heated rear window & cabin heating	25.0	8.0 (32%)
Heated rear window & cabin heating & lights	25.6	8.6 (34%)

To sum up, the measured electric consumption ranges from a minimum of 13.1 kWh/100 km to a maximum of 30 kWh/100 km with an average of 19.4 kWh/100 km over the 42 tests. The maximum electric consumption is obtained in two cases:

- driving the car in summer with air conditioning over an urban cycle with very low average speed (intense traffic conditions, test 28 of Table A2);
- using all winter auxiliaries over a mixed urban/extra-urban cycle with an average speed of 30 km h^{-1} (intense traffic conditions + extra-urban route, test 39 of Table A2);

However, the same kind of cycle (urban, mixed or extra-urban) with the same combination of auxiliaries can give a very different electric consumption according to its specific speed-acceleration profile. In particular, cycles 38 and 39 of Table A2 are both mixed cycles with "winter auxiliaries ON" but the corresponding electric consumption is 20.5 kWh/100 km and 30 kWh/100 km, respectively. Cycles 31 and 28 of Table A2 are both urban cycles with "AC ON" but the corresponding electric consumption is 20.1 kWh/100 km and 30 kWh/100 km, respectively. There is too much variability in driving conditions (depending on weather, traffic, etc.) to assume that a particular auxiliary affects a specific cycle differently from another.

Bearing in mind that the actual amount of energy stored in the battery during a complete recharge was found to be 21 kWh in the recharge tests, the range of the Smart ED varies from 70 (13.1 kWh/100 km) to 126 km (30.0 kWh/100 km), with an average of 108 km. Note that the nominal electric consumption of the Smart ED on the New European Driving Cycle (NEDC) is 12.2 kWh/100 km [22], corresponding to a range of 135 km.

3. Production of electricity in Italy

According to data on the website of the Italian national grid operator (Terna) [25], the net production of electricity in Italy in 2013 is 277,380 GWh while the request is 317.144 GWh. The difference is supplied by importing electricity from neighbor countries as shown in Table 3. Most of this energy is produced by nuclear power plants [26].

The energy produced in Italy is divided into traditional and renewable sources according to the percentage in Fig. 4 [25]. In this figure, "Hydroelectric" takes into account all electricity produced by hydroelectric power plants including hydro-storage plants.

The mix of fuels used for the production of thermoelectric energy which represents approximately 66% of total, is reported in Fig. 5 (Terna [25]).

For the proposed methodology, it is necessary to associate to each thermal source the corresponding power plant technology, the only problem being the natural gas that can be burned either in conventional gas turbines or in combined cycle power plants. Based on the literature data of the major energy producers [25–28], the installed power can be allocated into the two production systems as

Table 3
Production and demand of electricity in Italy in 2013.

2013	GWh
Total net production	277.380
Import	44.331
Export	2.178
Foreign balance	42.153
Consumption pumping	2.389
Electricity demand	317.144

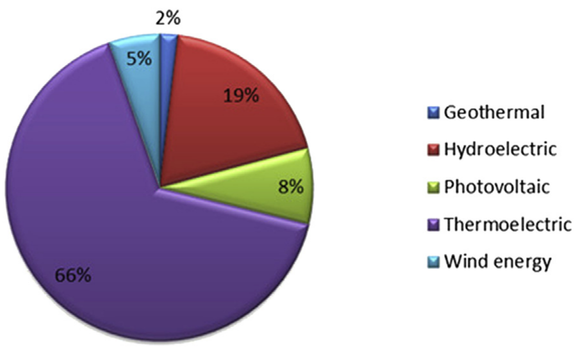

Fig. 4. Mix of technologies for electricity production in Italy in 2013.

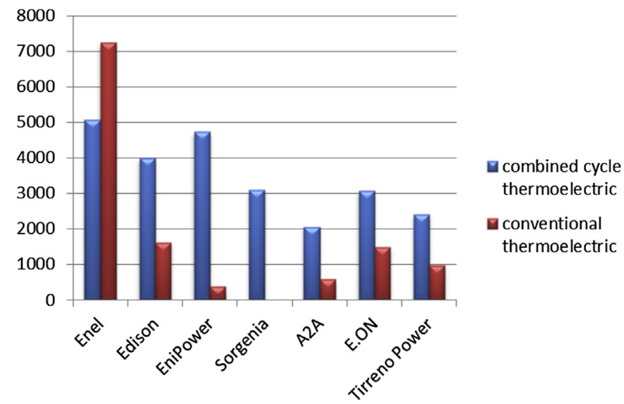

Fig. 6. Installed power (MW) of conventional and combined cycle thermoelectric power plants.

illustrated in Fig. 6. Note that 53% of the electricity produced in Italy from natural gas is obtained in conventional gas turbine power plants while the remaining 47% is produced by combined cycle power plants (this percentage rises to 63% if cogeneration is taken into account [25–28]).

3.1. Emissions levels of Italian electricity generation system

The emission factors of the production of electricity depend on the type of fuel, power plants and load level. To estimate their values, the maximum levels admitted for each technology by Italian legislation has been assumed for the nominal load [29]. The values at partial load have been extrapolated on the basis of the experience of P.R.I.M.E. partners including the Italy's largest power company, ENEL. The renewable energy power plants have been assumed to be 100% efficient (zero emissions). As already stated, embedded emissions (e.g., in the construction of Nuclear and renewable power stations are not considered) in the present investigation. The emission levels for pumped-storage hydroelectric power-plants have been obtained by assuming that the electricity required during the pumping phase is obtained from the grid for 8 h a day at the maximum load. The assumed values of the emission levels are shown in Fig. 7 for CO_2 and Fig. 8 for the other pollutant emissions.

In the period between July 2013 and November 2013 eight refills of a Smart ForTwo were carried out through the Enel recharging station located in the campus of the University of Salento. The date, time slots and adsorbed energy of each recharge have been registered and reported in Table 4.

To evaluate the corresponding emissions, the electricity generation mix at the specific date and hourly values of each recharge has been obtained from the Terna website [25]. Average values were also calculated as reference data. As an example, the daily diagram of electricity generation mix for the first recharge is reported in Fig. 9.

The data of Table 5 were obtained with the same procedure applied the other recharges. Details about the production of thermoelectric energy from different energy sources and in specific kind of power plants were not found in literature. To disaggregate the data of Terna about thermoelectric power plants into a specific fuel (natural gas, coal, oil, etc.), the average percentage of Fig. 5 were used. Except for natural gas, all fuels were assumed to be burned in conventional steam turbines. To disaggregate the natural gas data into a specific power plant technology, 47% of the electricity produced from this fuel was assumed to be transformed in combined cycle power plans, the remaining in gas turbine plants.

3.2. Load levels

The definition of the load levels is the most critical part of the proposed analysis for two reasons: the difficulty in finding literature data and the fast evolution of the electricity generation mix in Italy in the last years due to the unexpected increasing of electricity produced by renewable sources, mostly distributed wind farms and photovoltaic panels as registered by the *Italian Regulatory Authority for Electricity and Gas* (IRAEG) [30]. The website of the IRAEG was also valuable to retrieve information on the strategy used in Italy to meet daily and season peaks. Natural gas combined cycle power plants are mostly used for base load. Pumping plants are mostly used in Italy for the management of surges and daily peak demand [30,31].The diffusion of non-

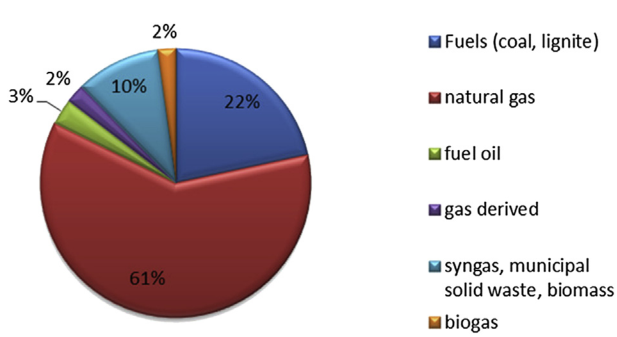

Fig. 5. Mix of fuels for electricity produced with thermoelectric power plants.

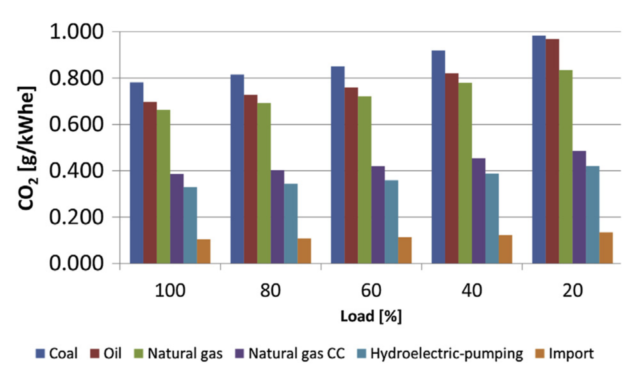

Fig. 7. Emission levels of CO_2 Italian power plants as a function of energy source and load level.

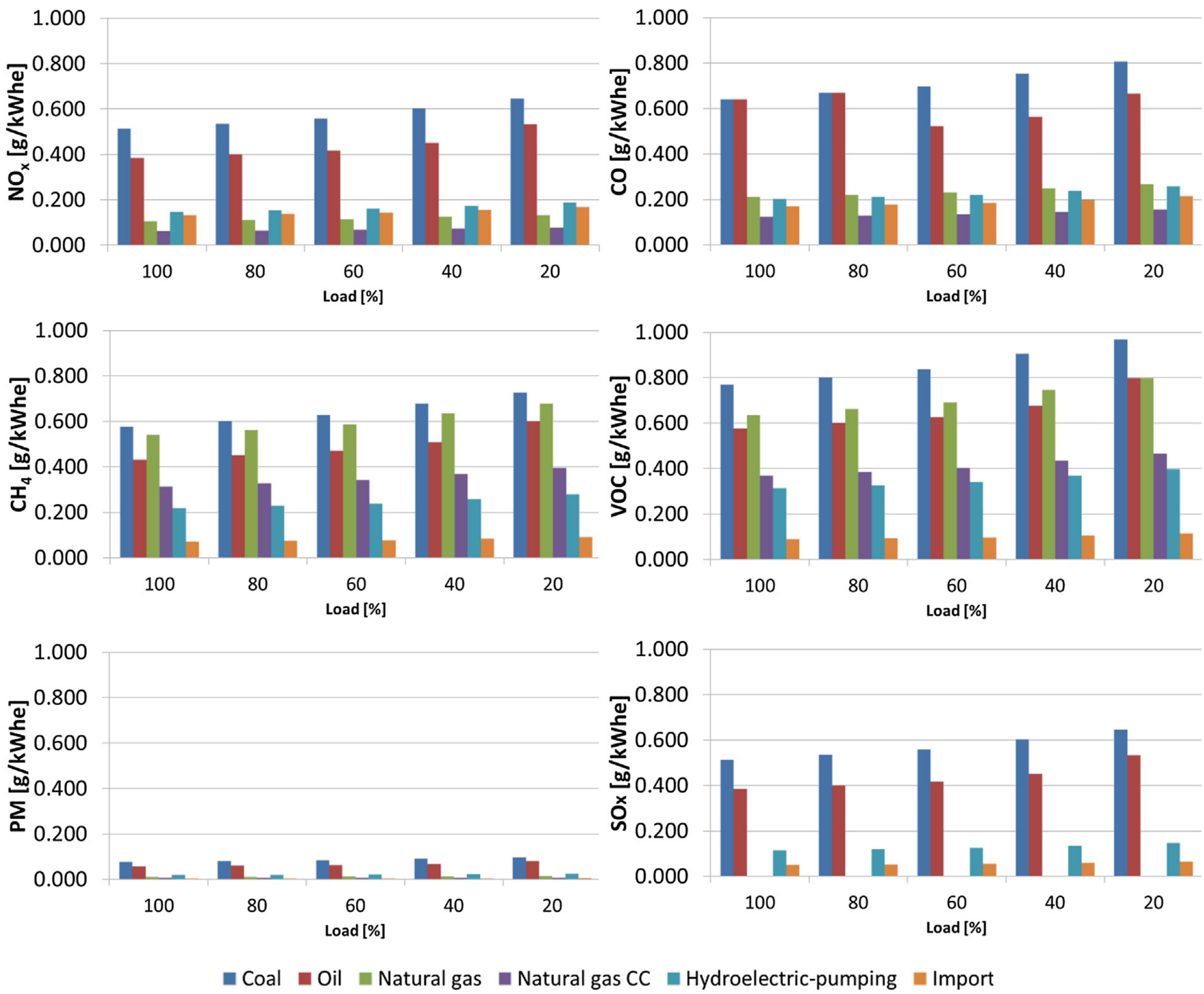

Fig. 8. Pollutant emission levels of Italian power plants as a function of energy source and load level.

programmable renewable sources intended for the production of electrical energy and distributed generation, has determined a different mode of operation of thermal power plants (with particular reference to Combined-Cycle Gas turbine), which were designed to cover the base load, but are gradually becoming installations used to follow the electric load [30]. They are required to work with more flexibility and consequently with a reduce efficiency as illustrated in Fig. 10 where the trend of efficiency for thermal power plants in Italy over the last decade is displayed [30]. According to IRAEG, the trend is to reduce the electricity generated by natural gas power plants.

In the present investigation, the load levels were defined according to three time slots: 1 am–8 am (night), 9 am–4 pm (morning/afternoon), 5 pm–12 pm (evening). To assign load levels the following assumptions were made:

- The trend of Fig. 10 suggests that combined cycle power plans in 2013 worked at high load (in fact their efficiency is quite similar to the maximum values achieved in 2004)

Table 4
List of the recharges.

Recharge ID (*j*)	Date	Time	Energy (K wh)
1	17 July 2013	11 am–5 pm	22,447
2	22 July 2013	10 am–11 am	2051
3	22 July 2013	11 am–5 pm	21,609
4	24 July 2013	10 am–5 pm	23,826
5	16 September 2013	12 am–5 pm	19,441
6	24 September 2013	11 am–1 pm	5,58
7	4 October 2013	1 pm–7 pm	20,244
8	28 November 2013	11 am–2 pm	8333

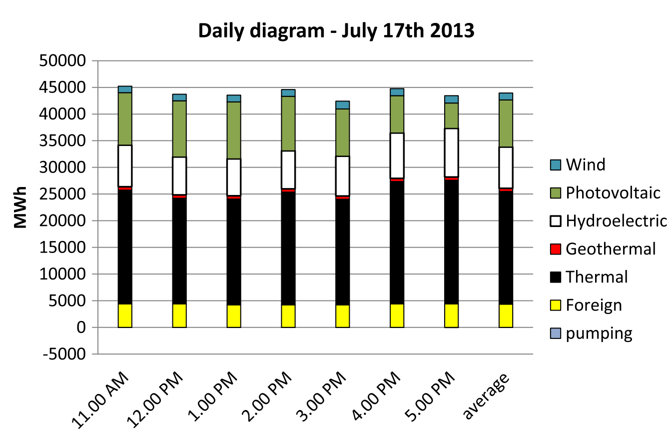

Fig. 9. Electricity generation mix for the recharge 1.

Table 5
Estimated electricity generation mix (MWh) for each recharge.

Recharge ID (*j*)	Geothermal	Hydro	Photovoltaic	Thermoelectric	Wind	Import	Pumping	Total
1	603.1	7730.1	9297.4	21133.1	1306.6	4350.8	−8	43944
2	603.5	9111.5	9143.5	19708.5	1111	4431.6	−1.5	44108.1
3	623.6	8524.1	9069.4	19854.0	1247.1	4350.8	−1.0	43668.1
4	618.8	8759.9	8515.3	23371.3	715.9	4360.9	−32.1	46309.8
5	605.7	4516.7	6848.3	20332.3	2405.0	3561.6	−529.8	37739.8
6	596.3	4198.0	10672.7	20914.7	509.0	3272.8	−149.3	40014.2
7	614.1	4582.9	2432.9	23950.1	771.0	5906.3	−151.0	38106.3
8	607.3	6790.8	4558.5	26524.8	1050.3	5262.3	−6.8	44787.1

- According to the same trend, gas turbines worked at low-medium load (being the efficiency in 2012 about 57% of the highest efficiency achieved in 2004).
- Steam turbines also show a reduction of efficiency (and so of load level) in the last decade. Moreover, natural gas power plants are preferred [30] to coal and fossil oils. Thus, their load level was considered always lower than 55%;
- The load levels of all thermoelectric power plants is considered lower in the morning/afternoon (larger contribution of renewable) and still lower in the night (low electricity request). Their load is assumed to be maximum in the evening when the request of electricity is high and the contribution of renewable sources is low [30].
- The daily peaks are assumed to be covered mainly with hydroelectric pumping-storage plants. However, they produce emissions only in the night when they are expected to work with very high loads (90%).
- Gas turbines are assumed to be used as “mid merit power plans”, i.e. to serve the extra demand for electricity which is seasonal [32]. Mid merit power stations are a compromise between base load power plants and peak loppers in terms of percentage of utilization [32].Accordingly, the minimum load for gas turbines was set equal to 50% in the present investigation.
- The level of operation of the units abroad, that provide a share of between 10% and 25% of electricity, needs Italian, was supposed to be consistently high (70%) during the whole day because they consist mainly of nuclear power plants [26].

The load levels for each technology and for each time slots presumed in the present investigation are reported in Table 6. Note that steam turbine power plants appear to have quick reaction times because of the large time slot (8 h) used in this investigation to classify the recharge timing. Lower time slots will be considered in the future and loads will be changed according to the actual reaction time of each technology.

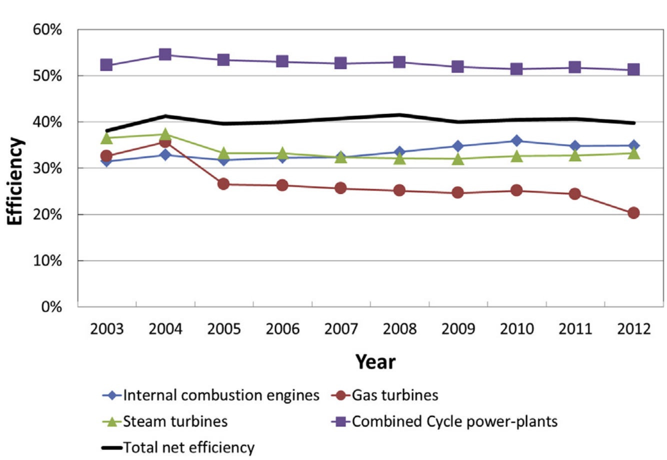

Fig. 10. Trend of efficiency of thermal power plants in Italy from 2003 to 2012.

3.3. Emissions factors of each recharge

Combining the data about time slots (Table 4), electricity generation mixes (Table 5), load levels (Table 6) and emission levels of power plants (Fig. 8), the emissions factors of each greenhouse/pollutant species, associated to each recharge have been calculated and reported in Table 7. An index “i” ranging from 1 to 8 was assigned to identify each greenhouse/pollutant species for the calculation used in the present investigation. The average values for each species “i” have been also computed and shown in the last row of the same table.

In the calculation of carbon dioxide, the amount derived from the combustion of gas, Municipal Solid Waste (MSW)/biomass, biogas has been also been considered. These fuels emit, respectively, the following quantities: 1.489 kg, 0.897 kg, 0.432 kg for each kWh produced [29]. They are supposed to be converted always at full load (100%). However, biomasses and biogas could be considered carbon-neutral and the contribution of Municipal Solid Waste could be taken into account at 50% [29].

4. Environmental impact of the electric vehicle (PTW)

In the proposed methodology, the PTW emissions of an electric vehicle are computed with the following formula:

$$X_i = \mathrm{EC}\cdot \mathrm{EF}i,\ \ j\cdot \mathrm{CF}_G\cdot \mathrm{CF}_R \tag{8}$$

where:

- “i” is the index of greenhouse/pollutant species (as reported in Table 7);
- “j” is the recharge ID (Table 5);
- EC is the electric consumption measured in kWh km;

Table 6
Estimated load levels.

	Time slot		
Power plant	1am – 8am	9 am – 4 pm	5 pm –12 pm
Coal	40	50	55
Oil	40	50	55
Natural gas turbine	50	55	60
Combined cycle	80	80	90
Import	70	70	70
Hydroelectric-pumping	80	0	80
Renewable	40	90	40

Table 7
Estimated emission factors for each recharge and average values.

Recharge ID (*j*)	Species ID (i)							
	1	2	3	4	5	6	7	8
	CO_2 [kg/kWe]	CO [g/kWe]	PM [g/kWe]	NO_x [g/kWe]	VOC [g/kWe]	CH_4 [g/kWe]	Metals [g/kWe]	SO_x [g/kWe]
1	0.3493	0.1523	0.0128	0.1054	0.2672	0.2169	0.0076	0.0702
2	0.3305	0.1429	0.0119	0.0990	0.2491	0.2022	0.0071	0.0657
3	0.3349	0.1451	0.0121	0.1006	0.2534	0.2057	0.0072	0.0668
4	0.3621	0.1581	0.0134	0.1093	0.2795	0.2268	0.0080	0.0732
5	0.3785	0.1667	0.0142	0.1153	0.2952	0.2390	0.0084	0.0777
6	0.3686	0.1597	0.0137	0.1102	0.2859	0.2321	0.0081	0.0744
7	0.4363	0.2027	0.0167	0.1407	0.3501	0.2841	0.0100	0.0928
8	0.4138	0.1868	0.0157	0.1292	0.3290	0.2670	0.0094	0.0863
Average		0.1643	0.3718	0.0138	0.1137	0.0759	0.0082	0.2887

- $EF_{i,j}$ is the emission factor of pollutant species *i* (in g kWh^{-1}) during recharge *j* according to the values of Table 7;
- CF_G is a dimensionless correction factor that takes into account the losses of energy in the national grid, assumed to be 1.0 according to Terna report for years 2011 and 2012 [25];
- CF_R is another dimensionless correction factor to allow for the losses of energy during the recharge. As discussed above, the correction factor CF_R was found to be 1.1 in average with a peak of 1.14.

4.1. Emissions of CO_2

A report from the International Energy Agency, [33] indicates for Italy an average emission of 406 g of CO_2 per kWh of electric energy in 2010. The trend of emission factor for CO_2 in Italy over years, as found in Ref. [29], is reported in Fig. 11. Note that the values obtained in the present investigation for recharges 1–5 (Table 7) with the proposed CO_2 emission factors (Fig. 7) ranges between 306.4 and 359.9 g kWh^{-1}. These values are below the expected average value for 2013 according to the trend of Fig. 11. However, these recharges were performed in Summer and in the morning when the contribution of energy from renewable sources is higher than in other seasons.

For a comparison to other countries, the emissions factor for year 2010 [33] are reported in Table 8. Note that Italy in an intermediate position between the two extremes being the emission factor of CO_2 minimum for France and maximum for China.

To take into account the effect of electricity generation mix and driving conditions on CO_2 emissions, four cases were considered:

- *Nominal:* the electric consumption was set equal to the nominal value found in literature [22], i.e 12.2 kWh/100 km; the average emission factor over the 8 recharges are used (see last row of Table 7); no correction is used for the recharge.
- *Average*: the electric consumption was set equal to the average value over the 42 tests (19.4 kWh/100 km); the average emission factor over the 8 recharges are used (see last row of Table 7), the correction factor for recharge was assumed to be $CF_R = 1.1$.
- *Best case*: the vehicle was assumed to be run in the best conditions (test 12 of Table A2 where the electric consumption is 13.1 kWh/100 km) and to have been recharged with recharge $j = 2$ (where the emission factor of CO_2 is minimum), no correction is used for the recharge ($CF_R = 1.0$);
- *Worst case*: the vehicle was assumed to be run in the worst conditions (test 12 of Table A2 where the electric consumption is 30.0 kWh/100 km), to have been recharged with recharge $j = 7$ (where the emission factor of CO_2 is maximum) with the maximum measured recharge loss ($CF_R = 1.14$).

The losses on the grid were considered in all cases.

To compare the electric vehicle with conventional cars, the emissions of CO_2 obtained in the four cases are compared in Fig. 12 with the limits set by European commissions. EU Regulation No 443/2009 [34] sets an average CO_2 emissions target for new passenger cars of 130 g per kilometer to be phased in between 2012 and 2015 and a target of 95 g per kilometer that will apply from 2021 [34]. Note that, except for the worst case, the emission of CO_2 of the electric vehicle is much lower than the 2021 limit. The emissions found in the nominal case are quite similar to the best case. For this reason, the nominal case will not be taken into account in the analysis of pollutant emissions.

Furthermore, it can be noted that the fleet limits refer to the Tank-To-Wheel emissions while the proposed methodology calculates the PTT emissions for the electric vehicles (being their TTW CO_2 emissions assumed to be null). According to Sullivan et al. [35] the emission factor of CO_2 for gasoline and diesel fuel should be

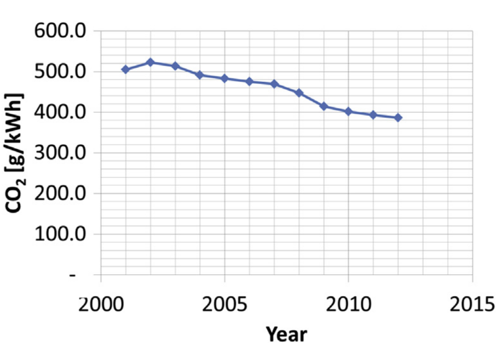

Fig. 11. Trend of emission factor of CO_2 in Italy.

Table 8
Emission levels of CO_2 from electricity in 2010 according to [33].

Country	gCO_2/kWh
Italy	406
France	77
Germany	461
UK	457
Europe	331
U.S.	452
China	766
World	565

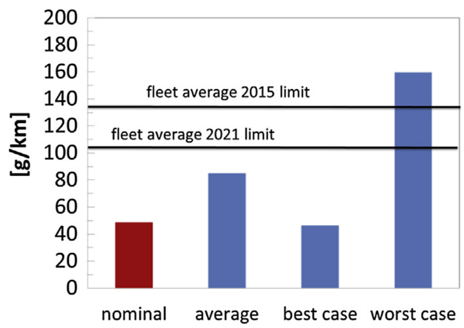

Fig. 12. Estimated emissions of CO_2 (PTW).

corrected multiplying the TTW emissions by 1.162 and 1.121, respectively, to take into account the production and transportation of the fossil fuels. Similar factors would be necessary for each energy source used to produce electricity in Italy. Since they are not available, the approach used in this investigation is Plant-To-Wheel for electric vehicles and Tank-to-Wheel for conventional passenger cars.

4.2. Pollutant emissions

The approach previously adopted for CO_2 has been applied to the pollutant emissions. The reference values for emissions were calculated as follows:

- *Average*: the vehicle consumption was set equal to the average value measured in the 42 tests i.e. 19.4 kWh/100 km; the average emission factor over the 8 recharges are used (see last row of Table 7), the correction factor for recharge was assumed to be $CF_R = 1.1$.
- *Best case*: the vehicle was assumed to be run in the best conditions (test 12 of Table A2 where the electric consumption is 13.1 kWh/100 km) and to have been recharged with recharge *j* (minimum emission factor for each pollutant substance); no correction is used for the recharge ($CF_R = 1.0$);
- Worst case: the vehicle was assumed to be run in the worst conditions (test 12 of Table A2 where the electric consumption is 30.0 kWh/100 km), to have been recharged with the recharge corresponding to the maximum emission factor for each pollutant substance ($j = 7$) and with the maximum measured recharge loss ($CF_R = 1.14$).

The results of the proposed methodology in terms grams of carbon monoxide (CO), nitrogen oxides (NO_x), particulate and unburned hydrocarbons (HC) emitted per km are reported in Fig. 13. For each of these pollutant species, the limits set by European regulations (Euro VI) for diesel and gasoline vehicles to be registered since September 2014 [36] are also shown in the figure. These limits refer to emissions measured over the NEDC (ECE 15 + EUDC) with the chassis dynamometer procedure.

Note that emissions of CO, NO_x and particulate of the Smart ED are well below the legislative limits for passengers cars. The emissions of unburned hydrocarbon of the electric vehicle were obtained by totaling V.O.C and CH_4. They are below the limit values for conventional passengers cars only in the best case. Data in literature [37,38] show that real world emissions can be quite higher than those measured with the European procedure. In particular, Pelkmans et al. [38] found that a model year 2000 vehicle, which already complied with EURO 4 limits, may reach CO and NO_x emissions up to 10 times higher in real traffic compared to the NEDC cycle while fuel consumption and CO_2 emissions are generally underestimated by 10–20% in the NEDC. Moreover, Pelkmans et al. [38] found an increasing of 33% of HC emissions in real world tests with respect to NEDC cycle for small petrol

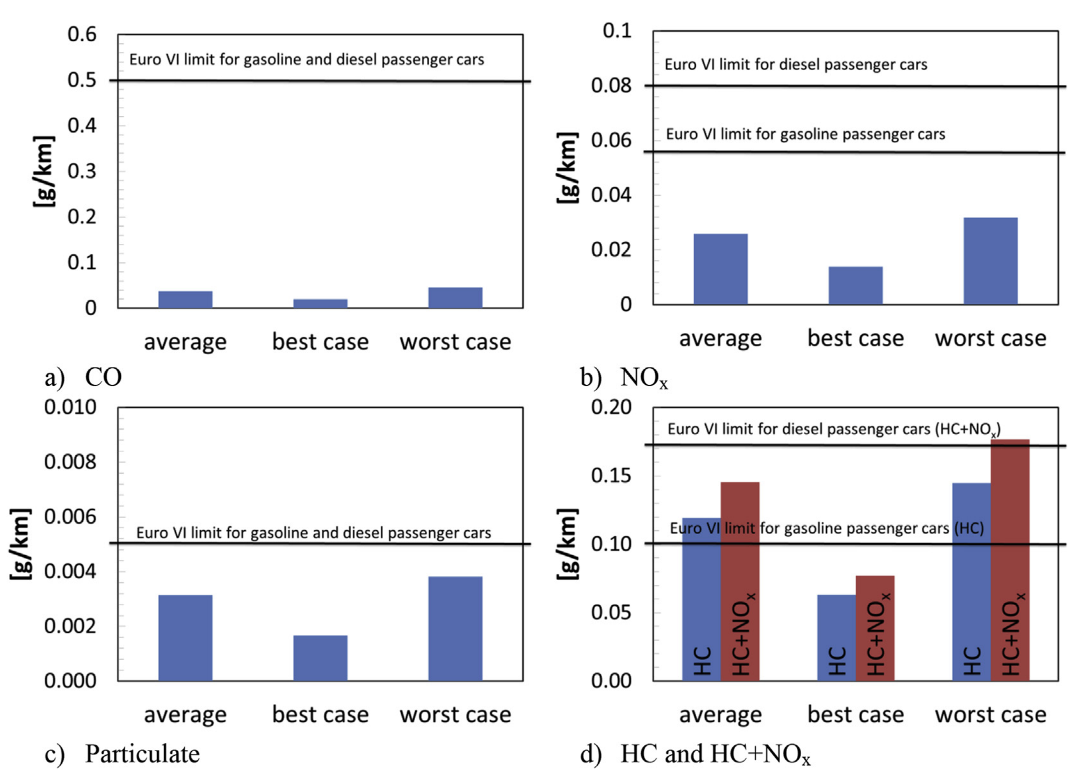

Fig. 13. PTW emissions produced by the electric vehicle.

passenger cars. So, it is not unreasonable to consider that electric vehicles are responsible for about the same emissions of HC of conventional passenger cars.

Further issues should be addressed in the future since electric vehicles are also responsible for emissions of SO_x and metals. Moreover, emissions associated to fuel production, tires and so on should be taken into account. As already explained the approach used in this investigation is Plant-To-Wheel for electric vehicles and Tank-to-Wheel for conventional passenger cars.

5. Conclusions

The paper presents a methodology to quantify the emissions of CO_2 and pollutant emissions from electric vehicles applied to a Smart ED tested for a period of 6 months in Lecce, Italy.

The first step of the methodology is the measure of the electric consumption on board of the vehicle on a total of 42 tests that differ for type of route, traffic conditions, use of auxiliaries (air conditioning, lights, heating, rear window heating). The results showed that the range of the Smart ED varies from 70 to 160 km (with an average of 108 km) along the 42 test. The measured electric consumption was then corrected to take into account the loss of energy associated to cooling of the batteries during the recharge. Specific tests have shown that this loss can be up to 14%. Moreover, the loss of electricity on the grid was taken into account using literature values.

The second step is the definition of the electricity generation mix of each recharging events. This information was obtained thanks to the ability of the recharging station to measure and store usage data. The corresponding mix of fuel and power plant technologies was obtained by official daily diagrams and average national data from the Italian national grid operator (Terna).

The third step is the evaluation of the emission levels, i.e. mass of pollutants associated to the production of 1 kWh of electricity from each technology in different days and time slots according to the corresponding load levels. The emission factors were estimated on the basis of literature data from the Italian Regulatory Authority for Electricity and Gas and experience of the authors.

The corrected electric consumption data are combined with information about electricity generation mix and emission levels to estimate the emissions per km associated to the use of the Smart ED. The results were compared with the limits set by Euro VI European legislation on conventional cars and showed the strong advantage of using electric vehicles instead of conventional in urban traffic conditions. In fact, real traffic emission of CO_2, CO, NO_x and PM emissions of the Smart ED are well below the European limits for conventional cars while HC emissions are quite similar. This is particularly true when recharge is performed in summer and in the morning when the electricity is mostly produced by renewable energy. The results refer to the Italian scenario (whose 60% of electricity is still produced with fossil fuel) but can be extended to any other countries with similar electricity generation mix.

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List of abbreviations

AC	air conditioning
BEV	battery electric vehicle
EC	electric consumption
$EF_{i,j}$	emission factor for species “i” during recharge “j”
GPS	global positioning system
HC	unburned hydrocarbons
ICE	internal combustion engine
IRAEG	Italian regulatory authority for electricity and gas
MSW	municipal solid waste
NEDC	new European driving cycle
NOx	nitrogen oxides
PM	particulate matter
PTW	plant-to-wheel
PV	photovoltaic
SOC	state of charge
SOx	sulfur oxides
TTW	tank-to-wheel
VOCs	volatile organic compounds
WTT	well-to-tank
WTW	well-to-wheel

Appendix A

Table A1
Vehicle specifications.

Engine/motor	Displaced volume	N/A
	Idle speed	0 rpm
	Maximum speed	5000 rpm
	Strokes	N/A
	Number of cylinders	N/A
	Max power	30 kW
	Nominal voltage	320 V
Tank	Tank volume	N/A
Battery	Capacity	20 kWh
	Numbers of cells	93
Gear Ratio	Gear 1	N/A
	Gear 2	N/A
	Gear 3	N/A
	Gear 4	N/A
	Gear 5	N/A
	Gear 6	N/A
	Final drive	8.67
Weight	Curb weight	900 kg
	Gross weight	1150 kg
Dimensions	Wheel base	1867 mm
	Frontal area	2.05
Drag (C_w)	Drag coefficient	0.37
Brakes	Brake piston surface	1800 mm^2
Tires	Inflation pressure front	2 bar
	Inflation pressure rear	2.5 bar
Wheels	Front wheels radius	263 mm
	Rear wheels radius	266 mm
Air Conditioning	Power consumption	Up to 3 kW
Performance	Max speed	Limited to 100 km h^{-1}
	Acceleration 0–100 km h^{-1}	N.A.
	Acceleration 0–60 km h^{-1}	6.5 s

Table A2
Complete list of tests.

ID	Energy usage (Wh)	Distance (m)	Type of cycle	Average speed (km h^{-1})	AC	Heating	Lights	Season	Consumption kWh/100 km
1	447.87	2022.32	Mixed	27.47	OFF	OFF	OFF	Summer	22.1
2	1832.01	11523.6	Mixed	33.58	OFF	OFF	OFF	Summer	15.9
3	1502.61	8790.04	Mixed	32.81	OFF	OFF	OFF	Summer	17.1
4	1337.23	6839.55	Extraurban	58.52	ON	OFF	OFF	Summer	19.6
5	3043.38	13449.63	Extraurban	67.99	OFF	OFF	OFF	Summer	22.6
6	800.19	4179.2	Mixed	27.83	ON	OFF	OFF	Summer	19.1
7	1580.43	7081.57	Urban	17.41	ON	OFF	OFF	Summer	22.3
8	1162.23	6983.39	Urban	14.13	OFF	OFF	OFF	Summer	16.6
9	1050.55	4131.78	Urban	27.46	ON	OFF	OFF	Summer	25.4
10	1823.71	9650.07	Urban	21.69	ON	OFF	OFF	Summer	18.9
11	1307.72	7908.78	Urban	20.48	OFF	OFF	OFF	Summer	16.5
12	478.79	3641.12	Urban	18.84	OFF	OFF	OFF	Summer	13.1
13	478.08	3451.97	Urban	21.69	OFF	OFF	OFF	Summer	13.8
14	674.96	4150.5	Mixed	29.9	OFF	OFF	OFF	Summer	16.3
15	1106.68	7140.91	Urban	16.15	OFF	OFF	OFF	Summer	15.5
16	1854.62	7364.31	Urban	14.84	ON	OFF	OFF	Summer	25.2
17	820.97	3987.14	Urban	30.95	ON	OFF	OFF	Summer	20.6
18	4027.52	16470.04	Urban	21.59	ON	OFF	OFF	Summer	24.5
19	3974.23	20503.95	Extraurban	68.66	OFF	OFF	OFF	Summer	19.4
20	2466.69	16537.78	Urban	20.52	OFF	OFF	OFF	Summer	14.9
21	1179.3	7610.2	Urban	27.78	OFF	OFF	OFF	Summer	15.5
22	1923.53	10345.79	Mixed	4.38	ON	OFF	OFF	Summer	18.6
23	3490.78	16313.19	Mixed	50.01	ON	OFF	OFF	Summer	21.4
24	4041.55	21596.48	Extraurban	74.87	ON	OFF	OFF	Summer	18.7
25	3413.69	21571.84	Extraurban	66.39	ON	OFF	OFF	Summer	15.8
26	3771.32	15804.6	Mixed	53.39	ON	OFF	OFF	Summer	23.9
27	2483.35	17826.53	Mixed	36.5	OFF	OFF	OFF	Summer	13.9
28	2224.33	7419.21	Urban	12.3	ON	OFF	OFF	Summer	30.0
29	1069.92	5311.74	Urban	10.65	OFF	OFF	OFF	Summer	20.1
30	2591.85	15314.19	Mixed	33.38	OFF	OFF	OFF	Summer	16.9
31	2445.35	12192.33	Urban	24.35	ON	OFF	OFF	Summer	20.1
32	3119.52	15429.11	Mixed	36.19	ON	OFF	OFF	Summer	20.2
33	2975.44	13990.06	Mixed	32.69	ON	OFF	OFF	Summer	21.3
34	643.07	3317.34	Urban	23.53	OFF	ON	OFF	Fall	19.4
35	928.02	3517.31	Urban	26.27	ON	ON	ON	Fall	26.4
36	1059.82	5984.53	Urban	31.63	OFF	ON	OFF	Fall	17.7
37	1784.79	10237.6	Mixed	41.32	OFF	ON	OFF	Fall	17.4
38	2099.22	10233.02	Mixed	44.83	ON	ON	ON	Fall	20.5
39	1333.16	4443	Mixed	31.53	ON	ON	ON	Fall	30.0
40	1845.3	7450.24	Urban	20.62	OFF	ON	ON	Fall	24.8
41	1639.99	8149.16	Mixed	41.98	OFF	ON	ON	Fall	20.1
42	1497.56	5987.44	Urban	33.83	ON	ON	OFF	Fall	25.0

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